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Shift from feeding to sustainably nourishing urban China: A crossing-disciplinary methodology for global environment-food-health nexus

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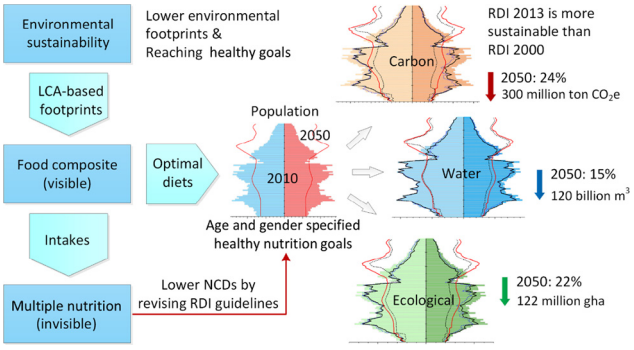
HIGHLIGHTS

- Urbanization systematically impacts Chinese health and the environment by dietary change.
- Dietary reference guidelines 2013 outperforms the previous 2000 in benefiting environment.
- Age- and gender-specific health goals should be highlighted when adopting optimal diets.
- Environmental benefits of optimal diets were scaled to dynamic population pyramids.
- A framework was proposed to nourish a sustainable world within planetary boundary.

GRAPHICAL ABSTRACT



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ABSTRACT

Dietary change is a win-win opportunity to address the nexus of health and the environment. To prevent city dwellers from developing non-communicable diseases, in 2013, China updated the 2000 version of nutrition-based dietary reference intake (DRI) guidelines. However, whether the DRI guidelines have a positive effect on the environment is not well understood. Here, we explored the systematic effects of urbanization on China's health and environmental nexus based on survey data. Then, we optimized the diets of 18 age-gender groups to reduce carbon emissions, water consumption, and land use while meeting the healthy nutrition goals of both DRI guidelines. The results showed that the optimal diets based on the DRI 2013 outperformed these on DRI 2000 in improving China's environmental sustainability, although these diets did not always perform better at an individual scale. Our findings suggest that dietary changes can reduce carbon, water, and ecological footprints by 24%, 15%, and 22% in 2050, respectively; however, the differences in age-specific and gender-specific health goals cannot be neglected.

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1. Introduction

China is facing the food-linked challenges of environmental stresses and soaring non-communicable diseases (NCDs) under urbanization

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(Bai et al., 2014; Cui and Shoemaker, 2018; Yang et al., 2013). Hypertension, diabetes, and stroke currently affect 226 million (Zhou et al., 2017), 110 million (International Diabetes Federation, 2015a), and 11 million (Wang et al., 2017) Chinese adults, respectively. Diets high in animal products and resultant overweight are the main causes (Yang et al., 2013; Zhou et al., 2016). For example, the Chinese per capita pork intake increased 4-fold and beef intake increased 16-fold from 1978 to 2012 (United States Department of Agriculture, 2017), contributing to the overweight of 279 million people (Ng et al., 2013). If this trend continues, an additional 50% more food will be needed in 2050 (Hamshere et al., 2014), when 76% of Chinese are estimated to be wealthier city dwellers (United Nations, 2014).

Unfortunately, urbanization in turn makes it difficult to close such a food gap. Firstly, cropland losses will continue in China due to rapid urban sprawl (d'Amour et al., 2017). Moreover, new evidence shows that a temperature rise will reduce maize and wheat yields in China (Zhao et al., 2017), and such changes are worsening because of the rising spatial inconsistency of land and water resources. Physical and virtual water transfers can alleviate the water scarcity of water-receiving regions (Dalin et al., 2014; Hoekstra and Mekonnen, 2012; Zhao et al., 2015; Zhuo et al., 2016) but at the great expense of exporting regions (Suweis et al., 2013; Zhao et al., 2015). Besides, carbon emissions give another constraint because China is still far from its promised goal of cutting carbon intensity by 40–45% from 2005 levels by 2020 and reaching peak levels before 2030 (National Development & Reform Commission of China, 2015b).

Alternatively, dietary change represents a breakthrough for this nexus of health and the environment (Alexander et al., 2016; Westhoek et al., 2014) because consumers can lower the carbon, water and ecological footprint (i.e., CF, WF, and EF, respectively) of food supply chains, which is quantified by life-cycle assessments (Hellweg and Canals, 2014; O'Rourke, 2014). For example, Tilman and Clark (2014) found that dietary changes could reduce the global carbon emissions and land use significantly, while lowering mortality from heart disease, diabetes, and cancer. Springmann et al. (Springmann) further showed that developing countries benefited the most from these dietary changes, especially East Asian nations.

To fight against NCDs, China updated its nutrition-based dietary reference intake (DRI) guidelines 2000 to 2013 version (see both DRI guidelines in Tables A1 and A2 of Appendix). However, professional nutrition knowledge is beyond the scope of public cognition. Thus, China released its food-based *2016 Chinese Dietary Guidelines* (Chinese Nutrition Society, 2016) to realize the DRI 2013 by helping the public make healthy food choices. Like most countries, China did not consider environmental sustainability when developing the food-based and nutrition based guidelines.

Behrens et al. (Behrens et al., 2017) included China's food-based guidelines for the first time in evaluating environmental impacts across 37 nations; and He et al. (2018) recently reported the deviation of Chinese changing diets from the 2016 guidelines and their environmental impacts. Focusing on the nutritional goals of the DRI 2013, our group has shown that dietary changes can cut carbon emissions of Chinese adults (Song et al., 2017). However, the effects of the revised DRI guidelines on the environment have not been studied especially compared with the old version of DRI 2000. Additionally, few studies have systematically investigated these links among diet and its environmental impacts, overweight, and related NCDs driven by urbanization.

By linking the China Health and Nutrition Survey (CHNS) (http://www.cpc.unc.edu/projects/china) database and the global LCA database of the Barilla Centre for Food & Nutrition (Barilla Center for Food & Nutrition, 2014), we aim to explore the following questions: (1) How does urbanization affect Chinese health, diets and related environmental sustainability? (2) Can weight loss benefit the environment and reduce NCDs? (3) What change trends are observed when different age-gender groups adhere to optimal diets? (4) Is the DRI 2013 more sustainable than the DRI 2000 at generating optimal diets?

2. Materials and methods

2.1. Food intake from household surveys

We extracted dietary data from four waves of China Health and Nutrition Survey (CHNS) in 2004, 2006, 2009, and 2011 (http://www.cpc.unc.edu/projects/china), with detailed information reviewed by Popkin et al. (2010) and Zhang et al. (2014). This study included 1.45 million records of the food intake of 22,684 respondents from 7283 households of 294 communities. Each respondent is linked with a household and community by a unique identifier. To avoid the impacts of demographic dynamics, we assigned respondents (households and communities) with multiple identifiers if they were surveyed repeatedly in multiple waves. Thus, this study included a total of 945, 19,053, and 45,271 'unique' communities, households, and respondents, respectively.

2.2. LCA-based environmental factors

All 1.45 million records of 1950 types of food intake were categorized into 28 food groups. For each group, we linked 18 nutrients with a global LCA database of carbon, water and ecological factors as reviewed by the Barilla Centre for Food & Nutrition (2014). However, the WF is unavailable for fish because most global seafood is captured from marine environments with "zero water" (Gephart et al., 2014). However, farmed fish in China generates a WF because of the consumption of water-intensive feed. We cited our recent estimate obtained using the von-Bertalanffy model to fill this data gap (Yuan et al., 2017). All environmental factors and uncertainties of the 28 food groups are summarized in Table A3 of Appendix.

2.3. Systematic impacts of urbanization

Urbanization is not a single ratio of the urban to rural population but rather includes multiple dimensions. Using the method of Jones-Smith and Popkin (2010), we measured the urbanization of each community according to twelve indicators of the CHNS. Then, we categorized all communities (including respondents and all food intake records) into 33 levels by applying equal intervals to the urbanization index. For each level, we quantified health and diet-related metrics as follows.

Referring to our previous study (Song et al., 2015), we calculated the average daily consumption of all 28 food groups based on records of food intake and a "person day" for each respondent, and we calculated the CF, WF, and EF embedded in food. We quantified the physical activity level and sedentary time of each individual based on their reports of occupations and schedules. The BMI was determined by body mass divided by the height squared, and the WC, total caloric intake and its component were downloaded from the CHNS, and these data were used to calculate the ratios of fat and carbohydrate energy to total calories.

2.4. Dual benefits of weight loss

To improve reliability, we stratified all adults as non-overweight and overweight groups using two criteria: the BMI (>24 kg m^{-2} for all adults) and WC (>85 cm for males and >80 cm for females), and all records of the CHNS dataset were stratified by these groups to calculate the food intake and its environmental footprint. Footprint uncertainties were quantified by Monte Carlo simulations, with 5000 trials per simulation. We compared the median of the CF, WF, and EF between non-overweight and overweight categories (by Wilcoxon rank sum tests, $p < 0.01$, $n = 5000$) because all footprints presented non-normal distributions (by Kolmogorov-Smirnov tests, $p < 0.01$, $n = 5000$).

We defined the presence of hypertension, diabetes, and stroke for each individual as a binary dependent variable, with overweight status, lifestyle, dietary energy and other demographic factors as independent variables. Then, we performed nominal logistic regressions to examine

the effects of weight loss on the risk of NCDs (see Nominal Logistic Regressions of Appendix).

2.5. Uncertainty optimizations

We categorized all respondents into 18 age-gender groups according to definitions in the DRI guidelines. For each group, we calculated the surveyed diets and their CFs, WFs and EFs as references. Based on the created links between nutrients and environmental footprints across all 28 food groups, we ran uncertainty optimizations for each age-gender group to produce optimal diets with three objectives.

We targeted a synergistic reduction of the CF, WF and EF. Notably, we defined the "synergy reduction" as minimizing the CF and not increasing the WF and EF compared with the surveyed diets, because our hundreds of experiments found that minimizing all three footprints for all age-gender groups under strict constraints was impossible. Moreover, to meet the health goals of all 18 nutrient intakes defined in the DRI guidelines, both the recommended intake and tolerable upper limit were used as constraints for each nutrient. Additionally, we added constraints for each food group to prevent a huge deviation from eating habits (see Uncertainty Optimization of Appendix).

2.6. Dynamic and spatial patterns

We magnified the individual environmental benefits of each age-gender group by population pyramids at multiscale. At the country scale, we compared the total environmental benefits of dietary changes in 2010 based on the DRI 2000 and 2013, and projected these benefits in 2050 based on optimal diets of DRI 2013. The population pyramid from 2010 was cited from China's 6th National Population Census by the National Bureau of Statistics (National Bureau of Statistics of China, 2010); the pyramid from 2050 was from the World Population Prospects projected by the United Nations (United Nations, 2015).

At the county scale, we linked the county population pyramid of China's 6th National Population Census (China Statistics Press, 2012) with the spatial boundaries of 2359 county polygons. For each age-gender group, we calculated the ratios of the county to country population in 2010, which was used to distribute the population pyramid of 2050 into counties, thereby generating population pyramids for 2050 at the county scale. We magnified the individual footprint reductions of alternative diets up to the county level and performed spatial hotspot analysis using the ArcGIS package from ESRI (www.esri.com).

3. Results

3.1. Nexus under urbanization

We measured the urbanization of each community using twelve indicators, with which all 294 communities with 15,734 surveyed respondents were categorized into 33 levels in ascending order of urbanization. For each level, we quantified the respondent's physical activity, body mass index, energy intake, and diet-related carbon emissions.

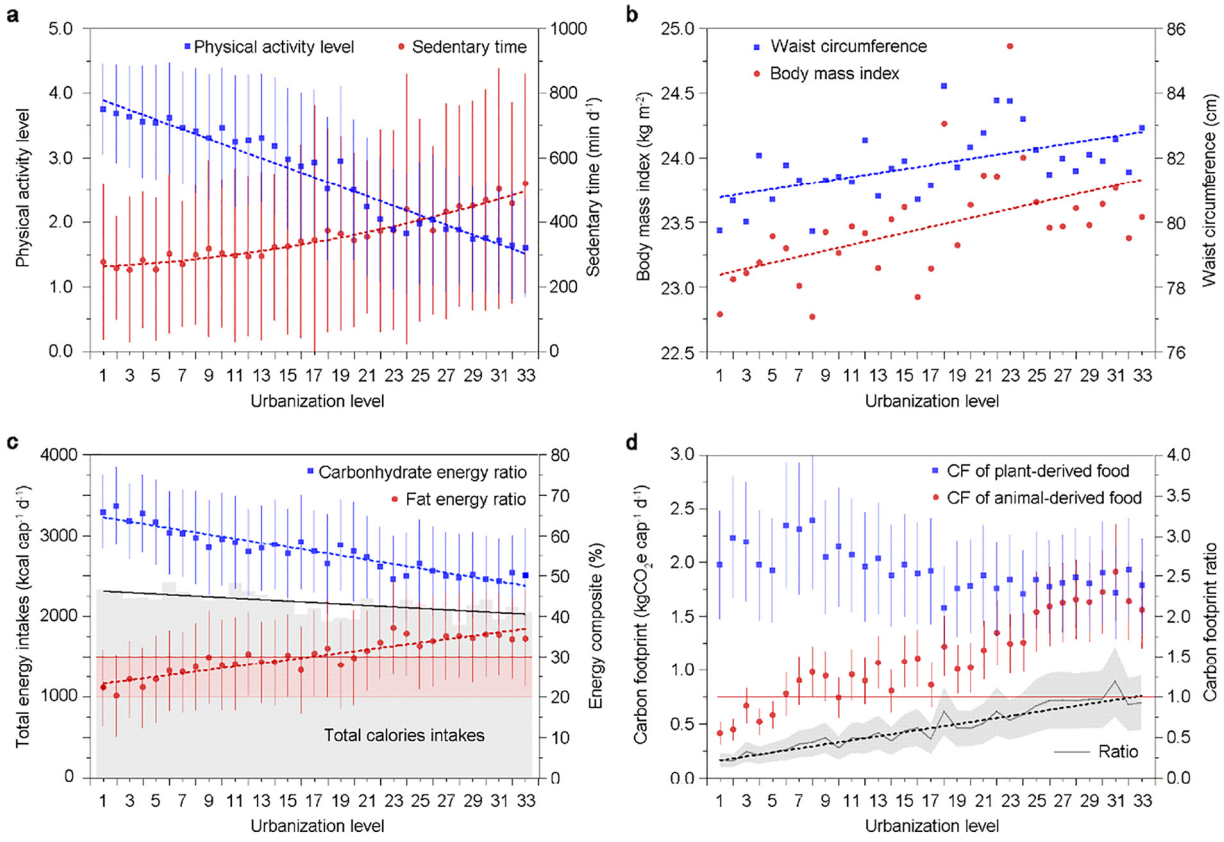

Fig. 1. Systematic impacts of urbanization on the nexus of health and the environment. a, Physical activity level and sedentary time. The blue dotted line fits to physical activity ($y = -0.07x + 3.96$, Adj-$R^2 = 0.96$, $p < 0.001$) and the red to sedentary time ($y = 1.67x^2 + 0.16x + 262.06$, Adj-$R^2 = 0.93$, $p < 0.001$). b, Body mass index and waist circumference. The blue dotted line fits to BMI ($y = -0.02x + 23.07$, Adj-$R^2 = 0.26$, $p < 0.005$), and the red to WC ($y = 0.06x + 80.71$, Adj-$R^2 = 0.30$, $p < 0.001$). c, Calorie intake and its composites. The grey background represents the total calorie intake, and the red area represents the permitted fat-energy ratio of 20–30%. The black line fits to total caloric intake ($y = -0.01x + 2.32$, Adj-$R^2 = 0.40$, $p < 0.001$), the blue dotted line to the carbohydrate-energy ratio ($y = -0.53x + 65.19$, Adj-$R^2 = 0.89$, $p < 0.001$), and the red line to fat-energy ratio ($y = 0.43x + 22.90$, Adj-$R^2 = 0.84$, $p < 0.001$). d, Diet related carbon footprint (CF). The shaded area is the CF ratio of animal-derived and plant-derived food intake, with uncertainties quantified by Monte-Carlo simulations. The dotted line fits the ratio to the urbanization level ($y = 0.02x + 0.20$, Adj-$R^2 = 0.93$, $p < 0.001$).

Fig. 1 shows that the average daily sedentary time of Chinese adults increases by 88% from 277 min in an early urban stage to 520 min in a high stage. Moreover, the level of physical activity declines by 57% due to more city job opportunities. Urbanization leads to overweight, reflected by an average 3% increase in the body mass index (BMI, from 22.78 kg m^{-2} to 23.54 kg m^{-2}) and an almost 4% increase in waist circumference (WC, from 79.75 cm to 82.92 cm).

The total energy intake (Fig. 1c) decreases slightly with urbanization, and a sharp decrease in the carbohydrate component of 24% is observed. However, fat energy rises rapidly and even exceeds the healthy limit of 30% of total calorie intake advised by the DRI guidelines. This change is harmful to the environment. For example, respondents at higher urbanization levels emit more greenhouse gases from the intake of animal products but less from vegetal foods. Thus, a rising CF ratio of animal-derived to plant-derived foods is observed (Fig. 1d).

3.2. Co-benefits of weight loss

We separated all respondents into non-overweight or overweight categories using the two criteria of BMI and WC. For each category, we quantified the CF, WF and EF of the surveyed diets. Then, using overweight as a binary independent variable, we performed nominal logistic regressions to examine the decreased risk of NCDs by weight loss.

Weight loss relieves diet-related environmental burdens (Fig. 2a–c). When categorized by BMI, non-overweight adults produce significantly less CF, WF, and EF per capita per day ($p < 0.01$; 3210 g CO_2e, 1.95 m^3, and 13.45 g^2) than their overweight peers (3247 g CO_2e, 2.01 m^3, and 13.89 g^2). The WC-stratified results further show that weight loss leads to a greater reduction in the consumption of water and land resources by males than females. However, this situation changes in terms of carbon reductions, which are negligible.

Weight loss lowers the risk of NCDs significantly by two to three times (Fig. 2d) because overweight adults with a BMI > 24 kg m^{-2} are more likely to suffer from hypertension, diabetes, and stroke than non-overweight adults, with odds ratios of 3.3 [95% CI: 2.9–3.6], 2.4 [2.0–3.0], and 2.2 [1.5–3.4], respectively. This result is supported by the WC-stratified observations among both male and female respondents. In addition to the overweight status, the factors urbanization, respondent age, and fat energy intake also exert significant effects on the presence of NCDs (see Tables A4–A6 of Appendix).

If these BMI-based benefits are magnified by China's population, then the weight loss related to dietary changes would eliminate the risk of hypertension, diabetes, and stroke in 69, 45, and 5 million patients, respectively. China would also reduce the associated carbon emissions by 3.52 Mt. CO_2e, water consumption by 6.04 Bm^3, and occupation of bioproductive land by 4.37 Mg ha annually.

3.3. Age-gender specified optimal diets

Weight loss is a visible manifestation of the co-benefit to health and the environment. However, dietary changes occur via non-visible nutrients that vary across age-gender groups. Supported by the DRI guidelines of 2000 and 2013, we developed 36 optimization models to generate win-win optimal diets.

The surveyed diets and their environmental impacts vary across age-gender groups (category A in Fig. 3, and in Fig. A1 and A2 of Appendix). Males (females) consume 722–1149 (698–1038) g cap^{-1} d^{-1} and present CFs, WFs, and EFs ranging from 2143 to 3424 (2107–3075) g CO_2e, 1408–2065 (1327–1893) L, and 9.49–14.57 (9.14–13.14) gm^2, respectively. Animal products account for 15–19% by weight and are responsible for 35–41% of the CF, 38–44% of the WF, and 48–54% of the EF. Pork, aquatic products, beef, and lamb account for 51–65% of the intake of animal products and 72–82% of the CF, 69–76% of the WF, and 71–82% of the EF. For vegetal foods, approximately 84–88% of consumed grams are from vegetables, rice and wheat.

All optimization models have feasible solutions for reaching health and environment goals (categories B and C in Fig. 3a and c, and in *Appendices* Fig. A1a and A2a). Across age-gender groups, compared with the surveyed diets, optimal diets based on DRI 2000 (2013) reduce the CF by 0–24% (2–27%), WF by 0–17% (3–26%), and EF by 3–24%

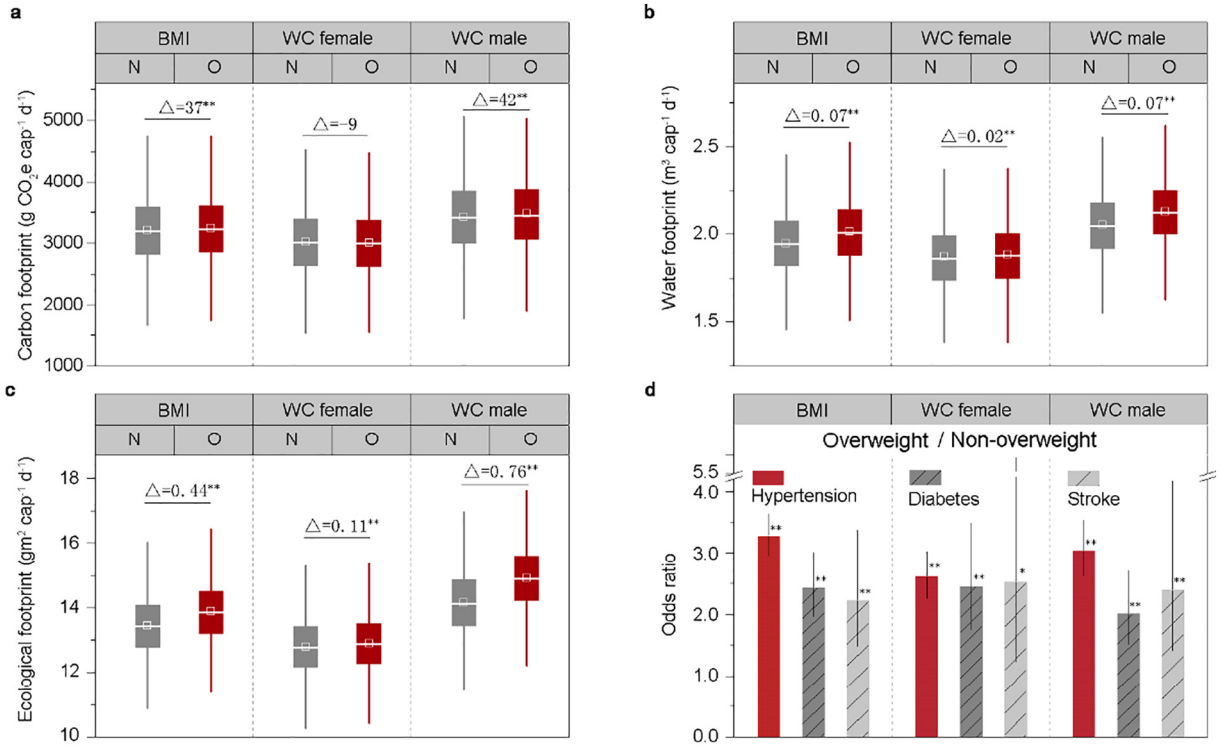

Fig. 2. Effects of weight loss on health and the environment. Categories N and O represent non-overweight and overweight, respectively. Uncertainties in panel a-c represent the 25th and 75th percentiles. △ represent the deficiency of the median. d, Odds ratios for the relative risk of hypertension, diabetes, and stroke of overweight to non-overweight people. **, and * represent the significance level of 0.01 and 0.05, respectively.

(3–30%). All alternative diets as expected lower the meat components of pork, beef, lamb, and aquatic products. Consequently, most diets increased the vegetal food intake, such as tubers, bread, and starches, to balance nutrition intake. However, none of the diets increase the rice intake, and this methane emitter was replaced by other items when optimizations.

We found that the DRI 2013 were more sustainable than the DRI 2000 in supporting most groups to achieve their win-win goals. However, this situation may vary, such as for males in the age 50~ brackets, for which the optimal diets associated with the DRI 2000 perform better. Moreover, for the DRI 2000 or 2013, lowering the proportions of rice, pork and aquatic products benefits the environment most, totally reducing the CF by 34–65%, WF by 25–53%, and EF by 34–62% across all age and gender groups.

3.4. Dynamic and spatial patterns

China is ageing and will have >370 million people over 60 in 2050 (Fig. A3 of Appendix), which is driving a shift in diet to increase food with specific nutrients, such as calcium, and thereby influencing

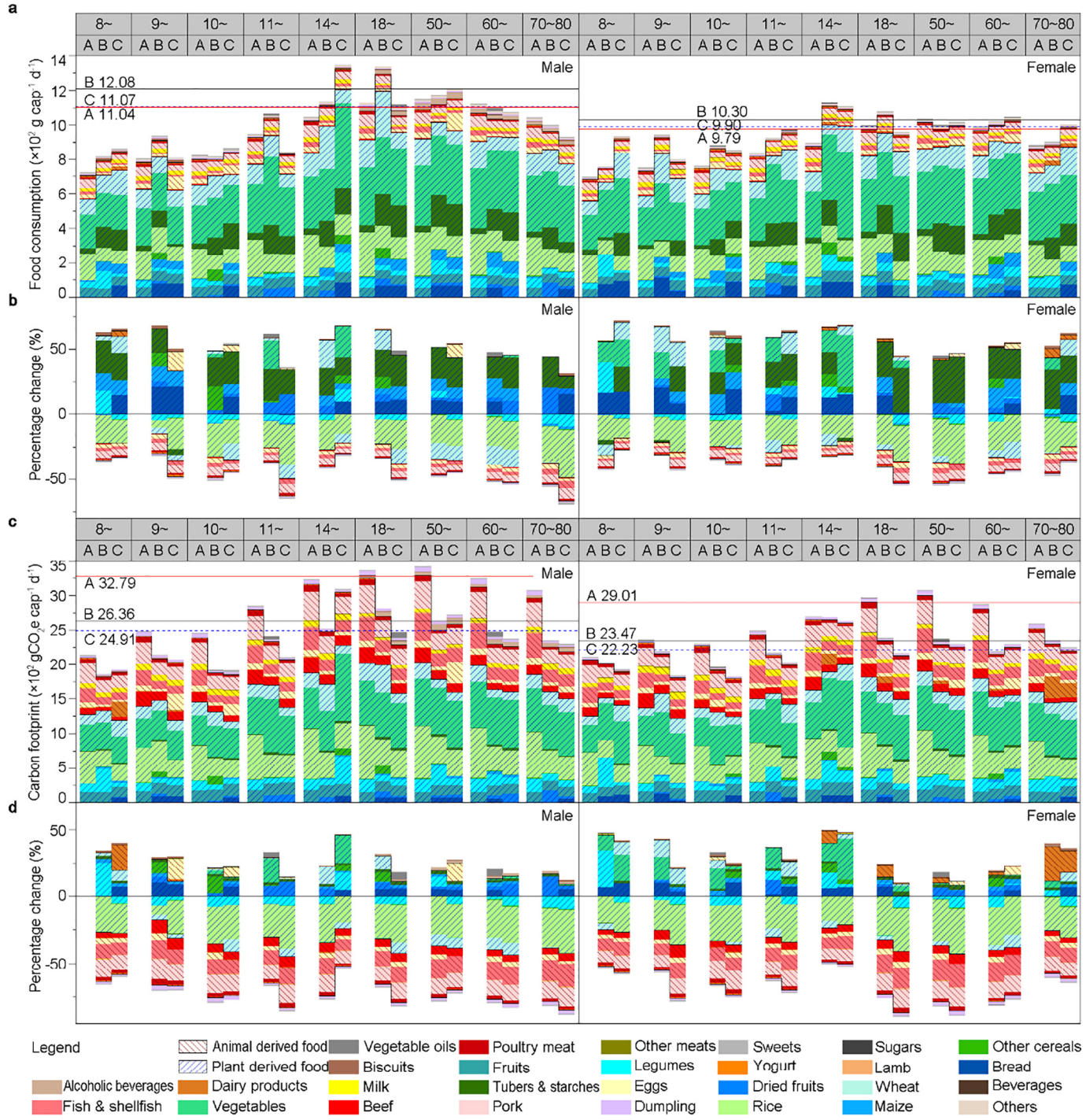

Fig. 3. Optimal diets to co-benefit health and the environment. a, Surveyed diets (category A) and optimal diets based on DRI 2000 (category B) and DRI 2013 (category C) for each age-gender group. b, Percentage contributions of each food group to dietary changes. Reference lines represent the sample-size weighted averages. c and d, Surveyed or minimized carbon footprints of (a) and (b), respectively, with synergistic reductions of water and ecological footprints shown in Fig. A1 and A2 of Appendix.

calcium-rich food supply chains and the associated environment. We scaled the benefits of optimal diets up to Chinese population pyramids to predict the potential of footprint reductions in 2050.

Fig. 4 shows that China generated CF, WF, and EF values of 1348 (234; [923, 1835]) Mt. CO_2e, 834 (77; [695, 988]) Bm^3, and 576 (40; [501, 659]) Mg ha on average (standard deviation; [CI: 95%]) in 2010, respectively, which accounted for 13%, 59%, and 13% of China's total CF (10,108 Mt. CO_2e) (World Resources Institute, 2017), WF (1400 Bm^3) (Mekonnen and Hoekstra, 2011), and EF (4490 Mg ha) (Global Footprint Network, 2017). For individuals of each age-gender group, the DRI 2013 are not always more sustainable than the DRI 2000 when producing optimal diets (Fig. 3), although they performs better for China. This finding is reflected by the results showing that the optimal diets based on the DRI 2000 (2013) lower the total CF, WF, and EF by 19 (24)%, 7 (17)%, and 15 (23)%, respectively, to average values of 1099 (1024) Mt. CO_2e, 773 (693) B m^3, and 577 (492) Mg ha annually.

If the diet patterns remain constant, then ageing China would produce a 1270 Mt. CO_2e CF, 781 Bm^3 WF, and 543 Mg ha EF in 2050. However, the optimal diets supported by the new DRI 2013 would reduce these metrics by 300 Mt. CO_2e, 120 Bm^3, and 122 Mg ha, respectively, which are much higher than the achievements gained from weight loss (Fig. 2). These emissions reductions are equal to the total carbon sink by planting 338 or 528 K ha of forest, referring to C stock density in tropical and temperate forests of 242 or 155 Mg C ha^{-1}, respectively (Pan et al., 2011).

China's population is unevenly distributed. About 80 years ago, Hu Huanyong, the father of China's population geography, proposed the "Hu Line", showing that 96% of Chinese live east of the "Hu Line" on only 36% of the country's territory. Today, a more striking fact is that approximately 42–55% of the potential reductions in the CF, WF, and EF from dietary changes are aggregated in 10–15% of China's territory. This result was based on the use of population pyramids of 2367 counties according to China's census in 2010 (see Fig. A4 of Appendix).

4. Discussion

4.1. Comparison with previous studies

Although nexus studies of dietary change are increasing, age-specific and gender-specific investigations are not common. Thus, we compared the percentage of our total environmental benefits with that in previous reports. Supported by optimal diets based on the DRI 2000 (2013), our reductions of 19 (24)% in the CF, 7 (17)% in the WF, and 15 (23)% in the EF are consistent with the reductions estimated by Behrens et al. (approximately 23% CF and 19% cropland uses) (Behrens et al., 2017).

In addition, the effect of dietary changes on increasing environmental health in most previous studies was greater than that observed here; for example, carbon emissions were cut by 25–40% (Westhoek et al., 2014), 30%, 45%, 55% (Tilman and Clark, 2014), and up to 29–70% (Springmann et al., 2015); water use was reduced by 20–44% (Zhuo

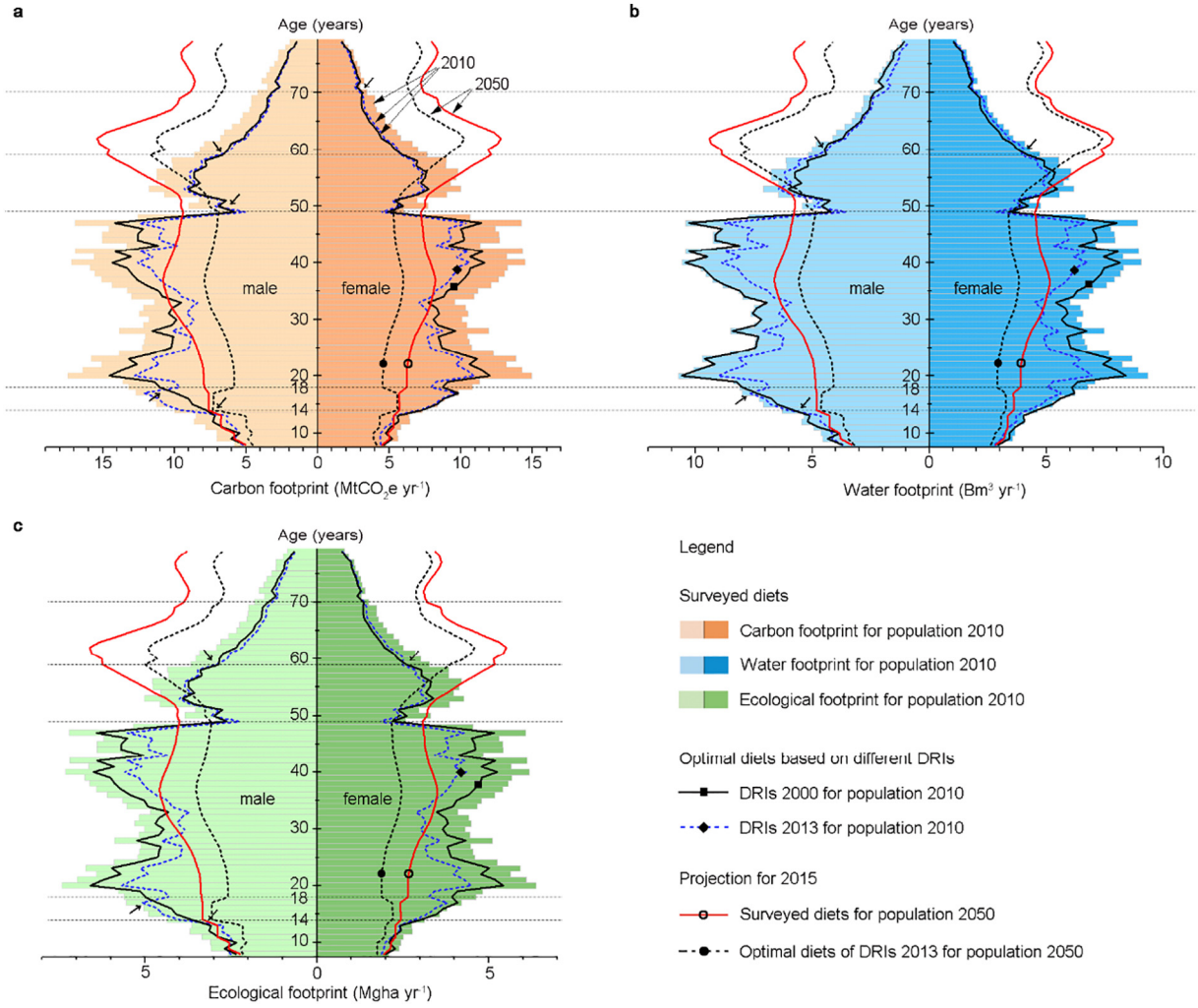

Fig. 4. Dynamic of environmental benefits based on optimal diets. a, b, and c, Carbon, water, and ecological footprints, respectively. The effects of revised DRI guidelines on the national total environmental benefits by optimal diets are equal to the areas between bands-curves or a pair of curves. Reference lines and short arrows represent the age thresholds and reflect the effects of the revised DRI guidelines on environmental sustainability under nutrition constraints for different age-gender groups.

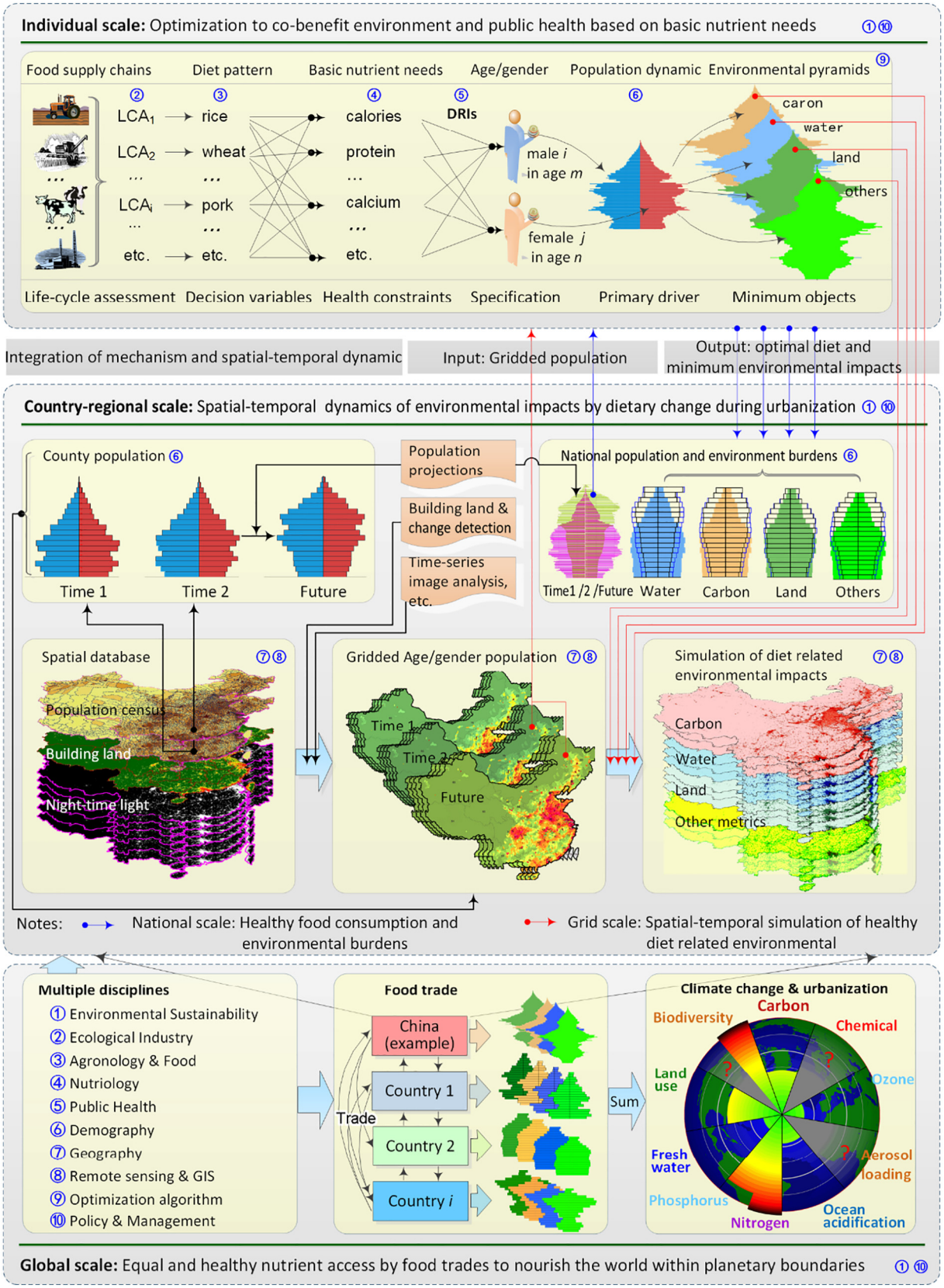

Fig. 5. Framework to nourish a sustainable world. At the individual scale, uncertainty optimizations minimize multi-environmental impacts while improving public health by reaching age-gender specified nutritional goals as defined by the dietary reference intake (DRI) guidelines; a life-cycle assessment (LCA) quantifies the environmental impacts of the food supply chain, with uncertainties included. At the country-regional scale, satellite images detect changes of built-up areas during urbanization, and a geographic information system (GIS) maps population patterns based on regional censuses of multiple periods or projections. At the global scale, each country trades food according to the optimal diets or nutritional needs of its population pyramid, on which human footprints of food are summarized to facilitate comparisons with planetary boundaries for multiple sustainable goals.

et al., 2016); and land use was reduced by 23% (Westhoek et al., 2014) and 55% (Alexander et al., 2016). Unfortunately, interpreting these differences is difficult because more than one factor co-varies across the studies on dietary change as reviewed by Hallström et al. (2015). Here, we discuss three general causes from a methodological perspective.

First, the diet scenarios of previous studies were cited from typical countries (Alexander et al., 2016), FAO projections or healthy guidelines (Springmann et al., 2015), and diets ranked by health risk (Tilman & Clark) and climate risk (Zhuo et al., 2016) or diets with assumed a lowering of animal product intake (Westhoek et al., 2014). Our diet scenarios, however, were not defined beforehand but were produced from optimizations of the DRI guidelines. Second, most previous studies focused on lowering a single impact, such as carbon emissions (Springmann et al., 2015) or water consumption (Zhuo et al., 2016), or addressed co-benefits to multiple environmental aspects (Behrens et al., 2017; Tilman and Clark, 2014; Westhoek et al., 2014) based on the awareness that diets lower in animal products are more sustainable. However, this study covered three footprints that are highly related to climate and urbanization, and the optimizations allowed us to address their trade-offs and proactively reach a synergistic reduction. Finally, previous studies appropriately used key nutrients, such as calories (Alexander et al., 2016; Springmann et al., 2015; Tilman and Clark, 2014; Westhoek et al., 2014; Zhuo et al., 2016), protein (Westhoek et al., 2014; Alexander et al., 2016; Tilman and Clark, 2014), and saturated fats (Westhoek et al., 2014), to represent average healthy goals or used food-based dietary guidelines as healthy nutrient alternatives (Springmann et al., 2015), whereas our study considered the healthy goals of different age and gender groups by using 18 nutrients as constraints for uncertainty optimizations.

4.2. Strength and limitations

This study found that urbanization systematically affects China's diet-related nexus of the environment and health by: Changing lifestyles, increasing the number of overweight people, degrading diets and nutrient intake, and multiplying environmental footprints. Weight loss, as expected, can dually benefit public health and the environment, whereas it is incomparable with the achievements gained by implementing optimal diets. Although the revision of the DRI guidelines can improve environmental sustainability, age-gender specified optimal diets are needed to reach the respective health goals. Our findings broaden the present scope of dietary changes that focus on adults or the average person. Additionally, by integrating the environmental benefits of dietary changes with population pyramid dynamics, this study deepens the current understanding of the static linkage between health and the environment (Heller et al., 2013).

This study has certain limitations. To fill data gaps, we cited the global LCA database, which is dominated by European and American agricultural systems and thus introduced uncertainties. We hope to provide more accurate estimates by using China's domestic data. Moreover, despite restraining the deviation of each food from the surveyed intake, we did not test the total deviations of these optimal diets from current eating habits. Minimizing these deviations deserves future attention because dietary change is a big challenge for many people. Optimal diets improved public health by reaching the nutritional goals of the DRI guidelines; however, we did not estimate the total decline in NCDs because a dose-response relationship between intake and health is objectively beyond our knowledge.

4.3. Perspective for environment-health nexus

Despite the challenges of climate change, China is still struggling to realize its urban dream for a better life. However, based on basic human needs (including nutrition), O'Neill et al. (2018) recently noted that humans must reduce resource density to live a good life within planetary boundaries. Our study is rooted in basic nutrient needs and corresponds to the insights of O'Neill et al. (2018); therefore, the findings are expected to provide a possible solution to China's nexus issue between health and the environment. But our study is far from the final solution because of overlooking one of the most important factors of food trade as recently reported by Wood et al. (2018), who found that food trade feeds more people by redistributing the surplus of global nutrients. For example, China ranks first level among importers of nutrients, such as calories, protein, iron, and calcium, thereby implying massive carbon, water, and land flows (Dalin et al., 2014, Dalin and Rodriguez-Iturbe, 2016; Hoekstra and Mekonnen, 2012; Weinzettel et al., 2013; Zhuo et al., 2016).

Therefore, system integration from local to global scales must be performed to realize sustainability (Liu et al., 2015), especially under the increasing challenges from urbanization—multiscale linkages between humans and environmental health, and related strong tradeoffs among multiscalar (Seto et al., 2017). Here, we put this China-contextualized study into global scale, and tentatively proposed a multidisciplinary framework to promote the nexus study on diet related health and environmental sustainability. The top-ten disciplines or key technologies were identified to promote academic discussions (Fig. 5).

Fig. 5 illustrates three topics that deserve in-depth investigation. First, it would be interesting to compare the environmental benefits of optimal diets at a global scale because the DRI guidelines vary across Chinese populations as well as across countries and ethnic groups. Second, nutrients determine public health while food is just a nutrient carrier. Thus, using nutrients to standardize the environmental impacts of food supply chains and trade would be helpful for addressing the health-environment nexus. Finally, integrating optimizations with systems dynamics may represent a good approach to investigating diet nexus issues driven by basic nutrient needs from ever-changing population pyramids.

5. Conclusions

The revised DRI guidelines for China provides the world with a unique example for exploring the diet-related nexus between health and the environment. Our findings demonstrated that urbanization systematically alters dietary patterns, nutrition intake, environmental sustainability, and physical fitness in China. Compared with the DRI guidelines of 2000, the new DRI 2013 expand the potential to benefit China's environment through dietary changes; however, these benefits depend on the adoption of age and gender-specific optimal diets. As a new agenda for food research approaches, the effects of diet deserve greater consideration to determine their ability to mitigate climate change while nourishing an urban world. We expect this study to contribute to global sustainability.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.08.040.

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